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COLD REGIONS ENGINEERED EARTHWORKS

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17. Abstract

A study was carried out to: a) document the current state-of-the-art of engineering earthworks in cold regions; b) to describe and evaluate on-going research in this field; and, c) to prepare a detailed outline, including cost estimates of a research and development strategy which would enable Canada to master the art of cold climate earthwork engineering. A detailed review of the literature was followed by discussions with engineers, contractors and equipment manufacturers experienced in northern work.

The study revealed that the various sectors of the engineering community involved with northern work in Canada are cognizant of the need for improved understanding of the geotechnical aspects of frozen soil earthworks and improved equipment capability. The need is variously described as "urgent", "important", "essential" and possessing the potential for a major "breakthrough" in technology. It is driven by the need for more cost-effective construction procedures, better equipment performance with less down time, and greater flexibility of construction schedules. In spite of this, there is very little current research or development activity related to this subject.

The incentive for Canadians to be able to have a larger role in the development of our own resources and associated infrastructure, and the possibility of export of technology and equipment to countries with a similar climate and similar development interests, justify a concentrated effort of research and development. A strategy to enable Canada to master the art of cold climate earthwork engineering is presented in this report.

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17. Résumé

Une étude a été faite visant à: a) faire un tour d'horizon des connaissances en matière de terrassement en génie civil dans les régions glacées; b) situer la recherche qui se fait dans ce domaine et en évaluer l'avancement et c) esquisser unde stratégie de recherche et développement assortie de devis estimatifs, permettant au Canada d'étendre sa maîtrise des terrassements de génie civil aux régions glacées. Une recherche documentaire exhaustive a été faite, suivie d'interviews personnelles avec des ingénieurs, entrepreneurs et fabricants de matériels de terrassement ayant l'expérience de ce type de travaux.

L'étude a mis en évidence le besoin généralement ressenti par ces personnes d'un approfondissement du domaine des terrassements et des fouilles en sol gelé, de ses aspects géotechniques et des matériels mis en oeuvre. Décrit comme urgent, important et essentiel, ce besoin peut déboucher sur d'importantes découvertes technologiques. Qu'il s'agisse de méthodes de travail plus économiques, de matériels plus performants et plus fiables ou d'un ordonnancement plus souple des travaux. Et pourtant, il se fait très peu de recherche appliquée ou de développement dans ce domaine.

Or, la perspective de pouvoir un jour jouer un rôle plus important dans la mise en valeur de ses richesses naturelles et dans la mise en place des infrastructures nécessaires, et de trouver des débouchés pour sa technologie et le matériel de sa fabrication dans les pays connaissant un climat analogue constitue, pour le Canada, une incitation à lancer un effort concerté de recherche et de développement dans ce domaine. Ce rapport propose une stratégie visant à mettre le Canada en mesure de maîtriser l'art des terrassements dans les régions glacées.

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SUMMARY

This report presents the results of a study of cold region engineered earthworks in Canada. The objectives of the study were:

(a) to document the current state-of-the-art of engineering earthworks in cold regions;

(b) to describe and evaluate on-going research in this field;

(c) to prepare a detailed outline, including cost estimates, of a research and development strategy which would enable Canada to master the art of cold climate earthworks.

The project was carried out by first conducting a detailed review of the literature relative to cold regions earthworks comprising excavation, handling and compaction and research related to the geotechnical aspects. This was followed by discussions, either in person or by phone, with a number of engineers and construction companies experienced in northern work. The Canadian manufacturers of construction equipment were identified and contacts were made with these organizations to assess the present equipment capabilities and to determine their views on the need and interest for improved cold regions capability in Canada and elsewhere. Known centres of northern civil engineering research in Canada, USA, Sweden and Norway were contacted to determine the present status of their cold climate earthworks research.

The study revealed that the various sectors of the engineering community involved with northern work in Canada are cognizant of the need for improved understanding of the geotechnical aspects of frozen soil earthworks and improved equipment capability. The need is variously described as "urgent", "important", "essential". It is also believed that R & D in this field could lead to a major "breakthrough" in technology. The requirement for R & D in this area stems from the need for more cost-effective construction procedures, better equipment performance with less down time, and greater flexibility of construction schedules. Most of the people contacted have extensive experience and useful recommendations as to how cold regions engineering capability can be improved. In spite of this, there is very little current research or development activity related to this subject in any of the sectors.

The reason that research and development lags in this area of technology is insufficient incentive. The accelerating need for resource development and infrastructure in the Arctic could provide the incentive. A coherent development program with a specific focus is required.

The incentive for Canadians to be able to have a larger role in the development of our own resources and associated infrastructure, and the possibility of export of technology and equipment to countries with a similar climate and similar development interests, justify a concentrated effort of research and development.

A research and development strategy to enable Canada to master the art of cold climate earthworks is presented in this report. The recommended program can be pursued in five phases; cost estimates are included for each phase and for the overall project.

TABLE OF CONTENTS

1.	INTRODUCTION	1
	1.1 Study Objectives	1
	1.2 Background	1
	1.3 Organization of Report	5
2.	REVIEW OF EXISTING TECHNOLOGY	6
	2.1 Equipment	6
	2.2 Geotechnical Practice	8
3.	RECOMMENDATIONS	21

References

Appendix A Equipment Systems - A Review Check-List or Guidelines For Cold Regions Operations

Appendix B Draft Terms of Reference for Phase I of the Proposed Program

Appendix C Draft Terms of Reference for Phase II of the Proposed Program

Appendix D Draft Terms of Reference for Parts A, B and C of Phase II of the Proposed Program

Bibliography

LIST OF FIGURES

Figure 1 - Moisture Density Relationship and Compactive Effort Density Relationship For Clay

Figure 2 - Moisture Density Relationship and Compactive Effort Density Relationship for Silt

Figure 3 - Moisture Density Relationship and Compactive Effort Density Relationship For Sand

Figure 4 - Moisture Density Relationship and Compactive Effort Density Relationship for Gravel

Figure 5 - Standard Proctor Compaction Ratio Vs. Temperature for Four Soil Types

Figure 6 - Relationship Between Dry Density, Water Content, Temperature and $CACL_2$ Additive

Figure 7 - Development of Canadian Machinery and Techniques for Frozen Soil Earthworks

IN-SITU MACHINE TRENCHING

PERMAFROST EXCAVATION

BLASTING AND BACKHOE TRENCHING

1. INTRODUCTION

This report presents the results of a study of cold regions engineering earthworks in Canada. The study was carried out by a project team comprising Golder Associates, J.E. Rymes Engineering Ltd. and Drs. D.H. Shields and J. Graham of the University of Manitoba. Authorization for the study was issued by Mr. P.L. Eggleton, Executive Director, Transportation Development Centre (TDC), Transport Canada by means of Contract No. 4927, File No. 01465-410. The project officer on behalf of the TDC was Dr. L.A. McCoomb, Senior Development Officer.

1.1 Study Objectives

The objectives of this study were:

(a) to document the current state-of-the-art of engineering earthworks in cold regions.

(b) to describe and evaluate on-going research in this field.

(c) to prepare a detailed outline, including cost estimates, of a research and development strategy which would enable Canada to master the art of cold climate earthwork.

The project was carried out by conducting a review of the technical literature and by contacting and interviewing a number of engineers in research centres, consulting practice and industry organizations, principally in Canada, but in other countries as well. Contacts were also made with research groups in Norway and Sweden and translations of Russian literature relevant to the subject were reviewed. Contractors in the heavy construction industry and pipeline industry were contacted and discussions were held with selected manufacturers of construction equipment in Canada.

1.2 Background

Construction activities in Canada typically slow down significantly during the winter months. Seasonal employment is accepted as a matter of course by many construction workers. In most parts of the country, however, some activity continues throughout the winter, and indeed, over the past few years, construction activity remained at a high level year round. Winter pipeline construction practices are well developed and used extensively in Canada. Techniques for building construction during severe winter conditions are well established in Canada and are applied routinely by experienced contractors. The implementation of federal government winter works programs in the 1960's provided a strong incentive for winter construction works and triggered research and development projects that contributed to standards of practice that are now well established such as placing and

curing of concrete, masonry work, temporary hoarding and heating, welding and so on. The exception is cold weather earthworks where there has been very little advancement in technology, equipment development or construction practice over the past several decades. The problems that are identified today are essentially the same as those identified by engineers and contractors almost thirty years ago when mega projects at that time, such as the DEW-line and mid-Canada line were being built.

The need to be able to successfully construct earthworks under severe winter conditions is increasing. Much of Canada's mineral and petroleum resources lie in the Arctic and offshore Arctic regions. The infrastructure required to develop and market these resources will include new roads, railroads, airstrips, harbour facilities, pipelines, staging areas and communities. All of these require major earthwork construction and the luxury of summer construction is severely constrained by the shortness of the season and the unstable terrain conditions during the summer.

Several major Canadian projects in recent years have involved extensive earthworks, some of which had to be at least partly carried out during winter conditions using freezing or frozen soil. These include sections of the MacKenzie Highway and Dempster Highway, the Kelsey River Power Development, the James Bay Power project, Polaris Mine on Little Cornwallis Island and the Cyprus Anvil Mine at Faro, Y.T. Most of these works have been brought to a successful completion by reshaping and recompacting the earthwork when it is thawed or by selecting material such as gravel or bedrock which is reasonably stable after thawing even though it was placed and compacted in a frozen condition. All of the projects involving excavation, compaction and placement of frozen soil have been very costly, primarily because of poor equipment performance and excessive down time, the need for extensive compaction effort, and high maintenance costs.

Construction of earthworks in temperate regions is usually carried out in compliance with well-developed and proven specifications. The specifications may designate the required product in terms of density or they may designate a placement and compaction procedure that the designer knows will produce an acceptable fill. In either case, the objective is to produce an earthwork, whether it be a highway, railway, or airstrip embankment, a dam or dyke, with engineering properties that will satisfy the design requirement with respect to strength, stability, durability or containment. There are no similar standards for earthworks constructed of frozen soil even though the desired end objectives of strength, durability, stability and containment properties are identical. The reason that there are no standards or established procedures is that there has been no concerted effort to solve the problems that currently exist in excavating, transporting and compacting frozen soil.

The major problem with winter earthworks lies with the performance of equipment used to excavate borrow and compact fill. A second problem is the strength of the fill after it thaws but this problem does not exist if the fill material is thaw stable and if it is constructed

in such a way that it does not contain large voids. Successful fills have been constructed using well graded frozen gravels having a very low moisture content or low moisture content shales which are fissile and which break into a particle size distribution when blasted or ripped so that a low void ratio exists after the soil is placed and compacted. Ice rich soils cannot be used for fill unless they are stockpiled and allowed to drain over several thaw seasons. Other soils, such as heterogeneous tills, sands and dirty gravels cannot be used without extensive processing to produce a particle size distribution that will result in a relatively low void ratio when the material thaws. Hence, the available soils that can currently be used to construct adequate earthworks in a frozen condition is very limited and indeed totally absent in many parts of Canada's Northern regions. Equipment to excavate, transport and compact soil in a cold frozen environment is not produced in Canada.

Ideally, a compacted soil will possess engineering properties at least as good as those it possessed before it was excavated. Often the water content has to be adjusted to produce the optimum moisture content for the particular compaction procedure and equipment used for construction. Compaction is usually achieved by a kneading or vibratory action that breaks down lumps of material and ensures that large voids are filled. With the exception of rock or gravel, no effort is made to process the material other than by the action of the compacting equipment.

Similar techniques have been attempted with the compaction of frozen soil. The very high strength of frozen clods or lumps, however, resists breakdown and response to kneading action. It is not possible to adjust the water content. Gap grading renders vibratory compaction ineffective in as much as there is often insufficient fine particles to fill the voids between the larger frozen lumps. Attempts at mechanically processing frozen soil have largely proved unsuccessful. Crushers or ball mills rapidly clog and become inoperative.

In situ processing has proved to be more successful. Three airstrips constructed on the north slope of Alaska, under the direction of the US Corps of Engineers, used a process whereby the frozen soil was broken down to produce a well graded material. This was achieved by first cross ripping to produce a loose surface layer that was then subjected to several passes of a sheeps foot roller to break down the large lumps. After placement and compaction the fill was insulated to prevent thawing because of the need for early and continuous year round operation of the airstrip. These facilities have now provided adequate service for approximately five years. The major problem identified in their construction was the excessive wear and breakage of rippers used for excavation and the downtime experienced with the excavation, processing, hauling, placing and compaction equipment (1).

Unlike the USSR, Canada does not have major urban centres within our permafrost regions. Nevertheless there have been remarkable achievements in the development of the Canadian Arctic and sub-Arctic. The Alaska Highway, the Churchill Railway, the White Pass and Yukon Railway, the Dempster Highway, the DEW Line, the Mid-Canada Line, and

the communities of Churchill, Inuvik, Thompson and Yellowknife, the most northerly mine in the world on Little Cornwallis Island and several mine site developments, all rate as world scale projects and all represent remarkable achievements in Arctic and sub-Arctic development. Some of these achievements, particularly the older ones, were realized by non-Canadian engineering and construction forces. This fact does not reflect so much on the Canadian capability as it does on the financing of the projects. The country paying for the works usually expects and demands the right to have a major involvement in the design and construction of the works.

But not all of the engineering and construction skills and equipment have come from outside our borders. One of the most remarkable achievements of Canadian Arctic engineering and construction capability is the construction of the Dempster Highway. This little known, little publicized project rates as a world scale achievement in Arctic development. Much of it was constructed in severe Arctic conditions, over sensitive terrain, using marginal quality borrow material to produce a transporation facility that today provides a direct serviceable link between the Alaska Highway at Whitehorse and the MacKenzie Delta at Inuvik.

Having successfully completed a number of world scale projects in Northern Canada, it is, perhaps, instructive to take stock and assess what benefits have accrued to Canada. That we have gained year round ground access to some of the resource rich areas of our nation is beyond doubt. But, have we enhanced our capability as engineers, contractors, manufacturers of equipment and developers of Arctic regions in terms of improved technology and construction equipment? Our understanding of permafrost conditions and its engineering properties have advanced substantially over the past few decades but our ability to work with and use frozen soils to construct in the Arctic has not.

All of the previously mentioned projects represent unique but missed opportunities to advance Canadian technology, construction methodology and equipment for cold regions earthwork construction. Had the opportunity been seized, any one of these projects could have put Canada at the forefront in Arctic construction in the world. The cost of the research, monitoring, analyses and design modifications needed to establish design and construction procedures, and equipment modifications to improve performance and efficiency, would have been a small increment on top of the initial capital costs of any of these projects. The capital supporting development of several of the major Arctic projects originated outside Canada and it is not surprising that the operators were reluctant to pay for a research and development component that would only marginally benefit their project while substantially enhancing the Canadian capability. The Dempster Highway, however, was engineered, supervised and paid for by Canadians. Many contractors, both Canadian and foreign-owned were involved in its construction. That we missed the opportunity to experiment, research, monitor and subsequently develop the Canadian Arctic earthwork capability is of our own doing.

Ironically, the projects that have produced the greatest advancement of Canadian cold regions technology, have not yet been built. Specifically, the engineering work associated with the Canadian Arctic Gas Pipeline in the MacKenzie Valley, the Foothills Pipeline Alaska Highway Project and the Polar Gas Project have sponsored more research and have resulted in the publication of more technical papers and hence contributed more to the establishment of the Canadian cold regions capability than all other Canadian Arctic projects combined.

The fact that there has not been an orderly progression and evolution of cold regions earthwork capability with improved technology and construction procedures emerging from sequential major Arctic projects does not mean that the knowhow required to achieve improved capability in Canada does not exist. Indeed, this study has confirmed that a substantial capability to design and construct earthworks in the Canadian Arctic exists in all sectors of the technical community. The capability, however, has not been focused on cold regions earthwork because of insufficient incentive. Manufacturers and suppliers of construction equipment will normally "winterize" the standard equipment but the major design modifications to systems and metallurgy required to assure satisfactory performance in the most severe Arctic climatic conditions are not implemented because of the limited demand for such equipment in Canada.

There can be no doubt that the need for an improved capability to construct engineered earthworks in Canadian cold regions exists today and that the need will grow in future decades. A similar need exists in many other countries such as the U.S.A., Scandinavia, USSR and China. An orderly research and development program that will: (1) establish the technology to construct earthworks from frozen soil that will satisfy the required engineering properties, and (2) lead to production of equipment capable of doing so, will not only improve the efficiency and economics of construction in Canadian cold regions but will also provide opportunities to export technology and equipment to countries with a similar climate and similar development objectives.

1.3 Organization of Report

The following section, Section 2, presents a brief review of existing technology with respect to cold regions earthworks. It incorporates both the geotechnical aspects and equipment capability. References and a bibliography appear at the end of the report. A research and development strategy to enable Canada to take the lead in both manufacturing the equipment necessary for cold climate earthworks and in carrying out earthworks in the north is presented in Section 3 along with a phased schedule and cost estimate.

Appendix A presents a check list of equipment components requiring modification or special attention in order to be capable of operating for long periods under very cold conditions as opposed to the methods normally accepted to "winterize" construction equipment. Appendices B, C and D suggest Terms of Reference for contractors to undertake Phase I and II of the project.

2. REVIEW OF EXISTING TECHNOLOGY

The technology for dealing with excavating, processing and compacting frozen soils falls into two distinct categories. The first deals with the machinery and equipment which is used, and the second with construction procedures that produce the desired excavations and embankments.

2.1 Equipment

Construction projects in cold regions require conventional equipment such as bulldozers, shovels, backhoes and dumptrucks; additional specialized equipment for surface or face excavation of frozen soils; equipment for crushing and processing of loosened borrow pit material, and high capacity compaction.

This study has identified no Canadian manufacturers of conventional backhoe/loaders, track mounted loaders, draglines, scrapers or bulldozers. There is some assembly in Canada of front acting shovels, off-highway trucks and a limited range of rubber tired loaders. One Canadian company produces a well-regarded line of graders. Although there is some manufacture of compaction equipment, it is primarily related to building construction and backfilling of trenches. Equipment required for large earthmoving contracts is not made in Canada. There are two Canadian manufacturers of light tracked vehicles for movement over soft-ground; low capacity earthmoving equipment may be adapted to these vehicles.

Of the $2 billion spent annually in Canada on excavation and compaction equipment, only 10 to 12 percent is spent on equipment assembled or produced in Canada. The remainder is mostly manufactured in the United States to specifications which take little account of extended periods of very low temperatures and high winds encountered in the Canadian North. Most manufacturers can provide some information on cold weather operations, but this advice is commonly only suitable for normal winter conditions in the Northern U.S. and Southern Canada. "Winterization" normally includes attention to special lubrication, antifreeze, battery heaters, radiator shutters, etc. However, most operators of heavy equipment in the Arctic find that this level of preparation is insufficient. Considerable additional work, or "Arcticization", must be undertaken often on the job, and amounting at times to 30 percent of the initial cost of the equipment. This work includes special attention to: air systems and brakes; the cab to improve operator comfort and safety; the tires, tubes, tracks and rollers; and especially to highly stressed metal components which become brittle at low temperatures. A checklist or guideline for equipment cold regions operations outlined in Appendix A shows the components requiring detailed attention.

The alternative to this extra preparation is lengthy periods of machine down time in a highly expensive and demanding climatic environment. Spares must be brought in from suppliers in Southern Canada, or often from the United States. Delays are costly in terms of expense, productivity and employee morale.

It is highly desirable that specialized equipment for use in cold regions should be designed and developed by engineers having specialized knowledge and background of equipment designs and operations along with a solid working knowledge of the constraints and limitations imposed by the cold regions. There are numerous examples of the use of equipment in Northern Canada which was inadequately designed for cold regions work. The results were invariably unacceptable.

From the studies we have undertaken, it appears that Arcticization, operation and maintenance by experienced operators will produce reasonable performance and greatly improved availability from many pieces of conventional equipment. Thus it is clear that the technology of cold weather machine design is now understood, and is available for the design of the specialized equipment discussed in this report.

However, this specialized equipment does not presently exist. There are no machines currently available for continuous surface or face excavation, for crushing and processing frozen soils, or for high energy compaction. In the mid-1970's a large, heavy duty, wheeled ditcher was developed, tested and modified for trench digging for the Mackenzie Valley pipeline project. This machine was never put into commercial use, but its development led to significant advances in understanding the technology of cutting processes needed for excavating frozen soils.

Our studies have involved discussions with Versatile Corporation, Winnipeg; Champion Road Machinery Ltd., Goderich; Banister Continental Ltd., Edmonton, Canadian Foremost Ltd., Calgary; Atlas Hoist and Body Inc. and Bombardier Inc., Montreal; and other discussions regarding equipment availability. The report by Ward and Lukomskyj, suggested that government action should make manfacturers aware of equipment requirements, and encourage distribution of relevant equipment information to contractors (2).

The equipment manufacturers confirmed that essentially the same basic models produced for work in Southern Canada are produced for work in the north, with some customizing as previously described. Contractors, such as Tower Arctic, who have extensive high Arctic experience, report that poor equipment performance in very cold conditions presents a major constraint on scheduling of construction and results in excessive down time. Most of the problems experienced with Arctic construction are equipment oriented. There is a strong need for improved equipment to allow more flexible construction schedules and to minimize down time. In the Eastern Arctic most major earth moving equipment has to be transported by sea lift and this severely limits the length of the season. There is obvious merit in developing lighter equipment that can do the job and that can be transported by aircraft.

Canadian manufacturing firms have the capability to develop unique equipment and to market both nationally and internationally. Outstanding examples are Canadian Foremost Ltd., Bombardier Inc. and Champion Road Machinery Ltd. It is interesting to note that Champion recently bid on a project for the U.S. Military that reflected similar needs to those identified by this study.

It is anticipated that equipment designed for use in the Canadian Arctic would also be of considerable interest in more southern regions of the country including urban Canada. Its use would significantly extend the period of the year during which construction activity is possible. Currently, for example, most earthmoving in Western Canada must stop in late October/early November - most contracts do not permit placement of frozen soil. Yet our interviews have encountered several recent and forthcoming projects where late placement of fill had to be undertaken.

2.2 Geotechnical Practice

The compaction of soils in freezing conditions has been recently reviewed by Burwash and Clark (3). It updates an earlier study by Clark (4) wherein compaction characteristics of frozen soils were studied in the laboratory and observations of field compaction results under freezing conditions were recorded. The tests showed that the moisture-density relationship for frozen soils is substantially different from that for unfrozen soils. For a given compactive effort and water content, the dry density of a frozen soil is lower than that of unfrozen soils. The difference in dry density is larger for fine grained soils than for coarse grained soils; is larger at lower temperatures; and is larger if there is a time delay between placement and compaction.

The present study has undertaken an extended review of the available literature, and interviews with many engineers who have had experience with excavating and compacting frozen soil. The literature review concentrated on three aspects of frozen soils earthworks, namely i) excavation and handling (ii) fundamental behaviour of frozen soils during compaction, and (iii) current practice involving the use of frozen soils in construction. It was found helpful to start initially with the bibliographies in the Paper by Burwash and Clark (3), and the review chapters by Baker and Johnson, and by McPherson in the recent book on permafrost engineering edited by Johnston (5). Searches were then made in bibliographies prepared by the National Research Council of Canada on frozen ground excavation, transport and placement; on permafrost and building in the north; and on technical translations, mostly from Russian sources. Searches were also made as follows:

a) by computer in the NTIS and COMPENDEX data files

b) in the References Lists in appropriate Papers in the Canadian Geotechnical Journal, Geotechnique, Geotechnical Division ASCE, Proceedings of annual Canadian Geotechnical Conferences, International and Canadian Permafrost Conferences, and the ASCE Conference 1978 on Applied Techniques for Cold Environments.

In addition to the published sources, personal contacts were made with J.I. Adams (Ontario Hydro); J. Hill (RTAC); J.K. Torrance (Carleton Univ.); R.R. Foster (Wardrop Assoc., Winnipeg); S. McKay (Esso Resources Ltd., Calgary); T.H.W. Baker, J.M. Konrad (NRC); P.M. Jarrett (RMC); J.G. McPherson and J.B. Smith (Acres Consulting Services, Winnipeg); C.A. L'Ami and J.H. Ellis (Manitoba Hydro); A.S.E. Wojcik (1 CEU DND); F. Young and R.A. van Cauwenberghe (Manitoba Dept. Highways); L.D. Keil (Underwood McLellan, Winnipeg); J.J. Pare (Quebec Hydro); B. Ladanyi (Ecole Polytechnique, Montreal); W.M. Haas (Michigan Technical Univ.), F.E. Crory (CRREL), J.H. Jacobs, R. Johnson, D. Cook (DPW), D. Deveney (Gulf,) Jean Barthe (Tower Arctic), H.B. Banister (Banister Continental Ltd.), W.J. Deyell and M.L. Peterson (Foothills Pipelines (Yukon) Ltd.); A.D. Munro (Majestic Wiley Contractors Ltd.); Mr. J.M. Stanford (Petro Canada Resources Ltd.); W.L. Daniels (V.L. Horte Associates Ltd.).

These interviews were designed to determine the extent to which frozen soils are used in northern construction in Canada, and the techniques which have been found applicable and/or lacking. To this end, searches were also made of Papers describing embankment construction in Northern latitudes, even though the titles themselves contained no specific mention of compaction of frozen soils. In all, approximately 60 Papers were examined. Brief references were found to embankments and highway fills in Northern Manitoba, Alaska and the Yukon Territory. Contact was also made with the Norwegian Geotechnical Institute, the Swedish Geotechnical Institute and the US Army Cold Regions Research and Engineering Laboratory (CRREL).

The reports on excavation techniques are somewhat varied. It is generally reported that free draining granular soils with low moisture contents can be fairly easily excavated, perhaps even with shovels or front-end loaders. As the grain size decreases and the moisture content becomes higher, then excavation is more difficult. The normal procedure is ripping with a single ripper tooth behind a large bulldozer. This procedure causes considerable wear on the tooth, the grouser plates and track. The viability of blasting excavation is also variously described. It is usually slow, noncontinuous, and except in certain formations such as fissile shale, not effective.

Processing of the loosened soil is usually limited to attempts to break up loosened lumps of frozen soil with the tracks of a bulldozer or with a sheepsfoot roller. The objective is to achieve a wide range of "lump size", the lumps consisting of aggregates of frozen particles.

Although there is not a large body of field data available concerning attempts to achieve high placement densities of fill materials under freezing conditions, a significant body of research is available. Burwash and Clark compile and tie together much of the research work that has been undertaken during the last twenty years and draw conclusions on the present state of the art.

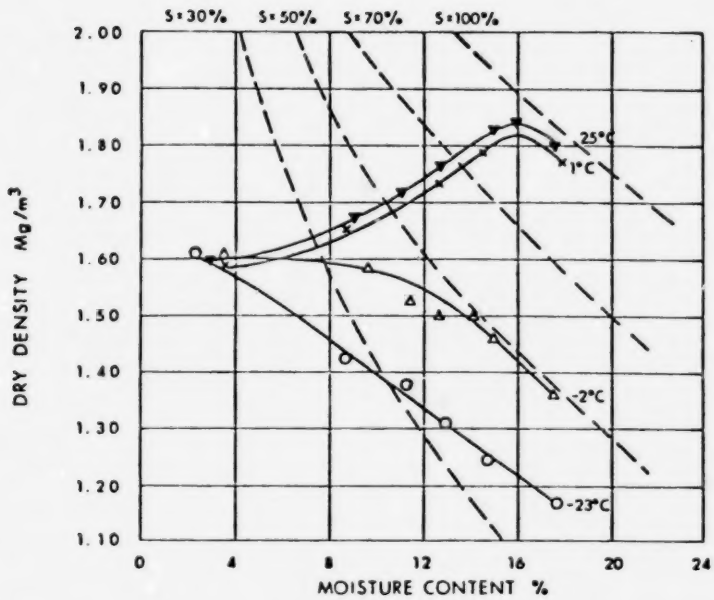
The effect of freezing temperatures on the moisture density relationship has been investigated by Clark for various soil types. The results of this study are reproduced in Figures 1 through 4 of this report. These figures show that the characteristic bell shaped curve for unfrozen soils does not occur for frozen soils. Instead, an increase in water content results in a decrease in dry density except for water contents well below optimum where little change in dry density occurs. For all four soils tested, the dry density at -23°C was less than that obtained at -2°C for moisture contents greater than 4 percent.

Figure 5 shows the relationship between Standard Proctor density ratio (dry density divided by maximum dry density at 25°C) and temperature for the four soil types which are each at their optimum water content. It is significant to note that the coarsest grained soil (gravel) gives the highest density ratio and the finest grained soil (clay) gives the lowest. The density ratio is also dependent upon moisture content as the highest density was obtained for gravel at a water content of 6 percent as compared to that of silt and clay at about 16 percent moisture content.

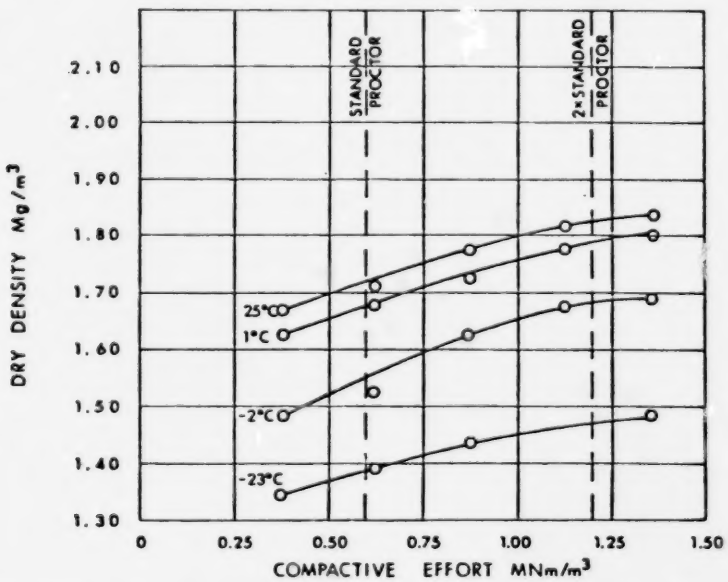
The degree of compaction that is attained using a frozen soil is directly related to the frozen strength of that soil. Frozen soil strength is influenced by many factors. These include temperature, texture, density, pore water chemistry and strain rate. Temperature is an extremely important factor with soil strength increasing dramatically with decreasing temperature. For coarse grained soils, the unconfined compressive strength increases with increasing water content. Finer grained soils have a more complex chemistry and hence trends are more difficult to identify. Generally, strength increases with increasing density but not necessarily with increasing water content. There is a tendancy, however, for samples at higher moisture contents to be more ductile and deformable than those at lower water contents, particularly at soil temperatures in the order of -2°C to -4°C.

Pore water chemistry is important because of the effect of unfrozen water content on soil strength. Unfrozen water content is generally a function of temperature, soil chemistry and pore water chemistry. Hence, a fine grained soil, with a larger amount of bound water, may be expected to have a lower strength than a coarse grained soil at equivalent density and moisture content. Similarly, the inclusion of chemical additive to depress the freezing temperature (i.e. calcium chloride) will increase the unfrozen water content and lower the soil strength.

A number of attempts have been made to increase the effectiveness of cold weather compaction. These include increasing the compactive energy, using additives to depress the freezing temperatures, and using varying methods of compaction.

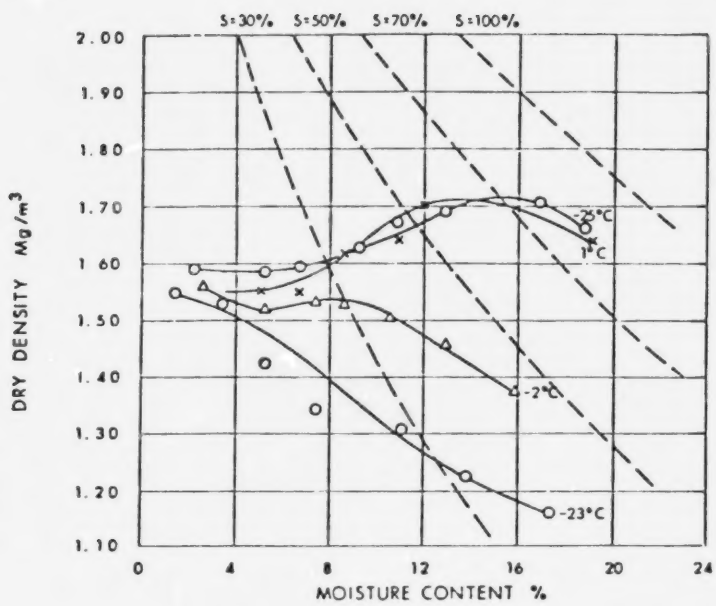


(a) MOISTURE-DENSITY RELATIONSHIP FOR STANDARD PROCTOR COMPACTIVE EFFORT

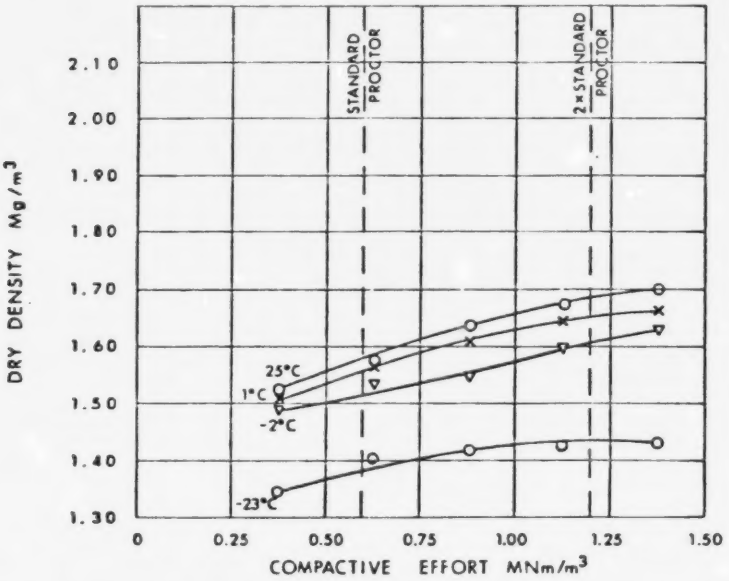


(b) COMPACTIVE EFFORT-DENSITY RELATIONSHIP FOR AVERAGE MOISTURE CONTENT OF 11.2 PERCENT

FIG. 1. MOISTURE DENSITY RELATIONSHIP AND COMPACTIVE EFFORT DENSITY RELATIONSHIP FOR CLAY (after Clark)

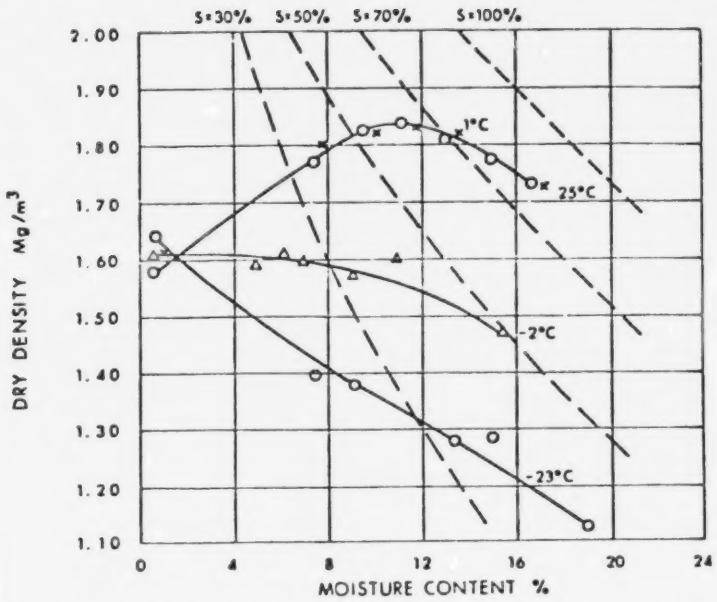


(a) MOISTURE-DENSITY RELATIONSHIP FOR STANDARD PROCTOR COMPACTIVE EFFORT

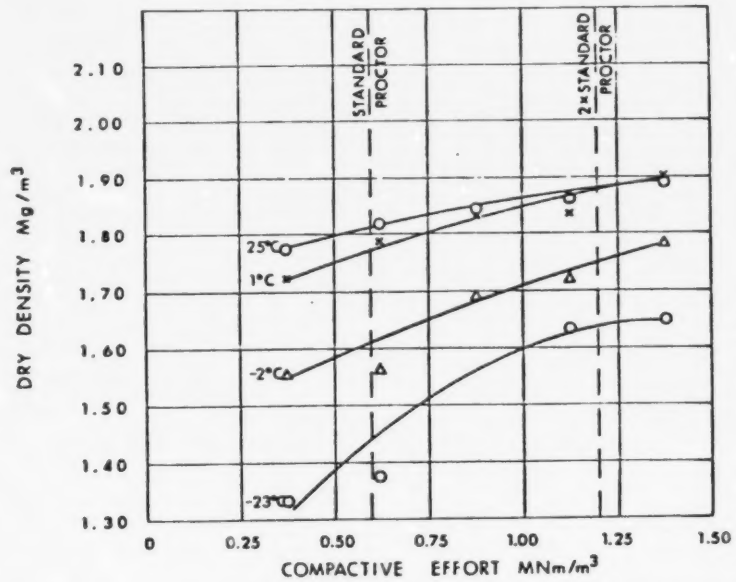


(b) COMPACTIVE EFFORT-DENSITY RELATIONSHIP FOR AVERAGE MOISTURE CONTENT OF 6.7 PERCENT

FIG.2. MOISTURE DENSITY RELATIONSHIP
AND
COMPACTIVE EFFORT DENSITY RELATIONSHIP
FOR SILT (after Clark)

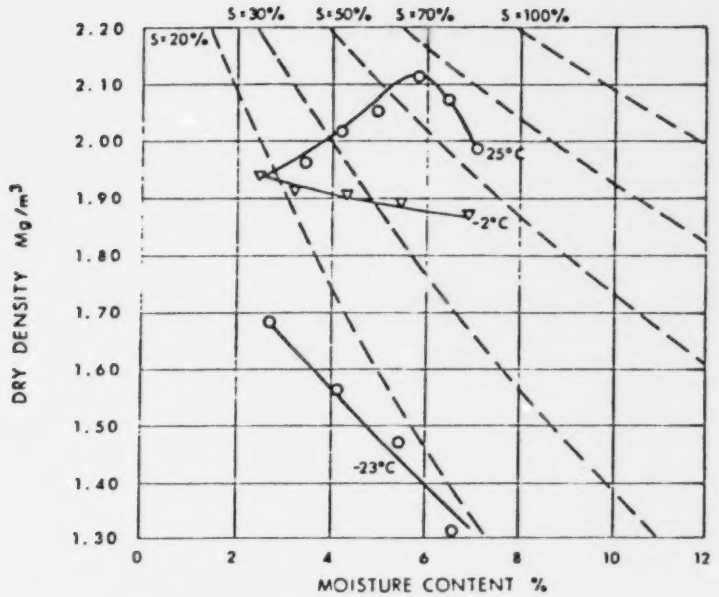


(a) MOISTURE-DENSITY RELATIONSHIP FOR STANDARD PROCTOR COMPACTIVE EFFORT

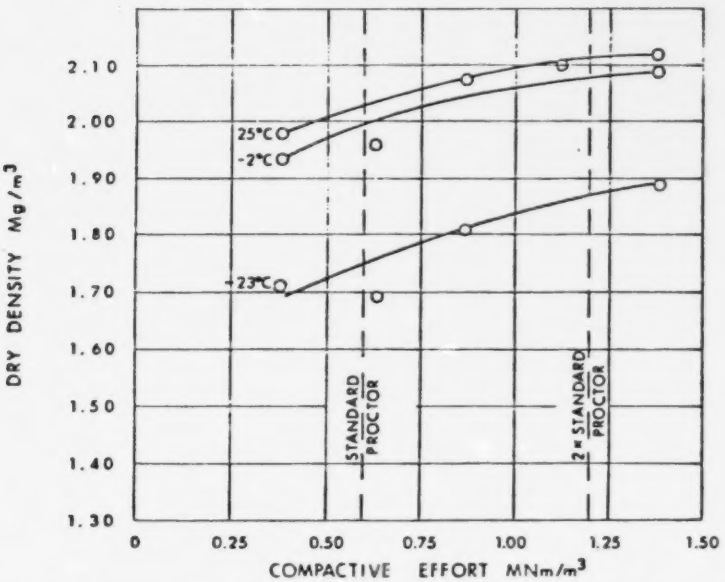


(b) COMPACTIVE EFFORT-DENSITY RELATIONSHIP FOR AVERAGE MOISTURE CONTENT OF 9.1 PERCENT

FIG. 3. MOISTURE DENSITY RELATIONSHIP AND COMPACTIVE EFFORT DENSITY RELATIONSHIP FOR SAND (after Clark)



(a) MOISTURE-DENSITY RELATIONSHIP FOR STANDARD PROCTOR COMPACTIVE EFFORT



(b) COMPACTIVE EFFORT-DENSITY RELATIONSHIP FOR AVERAGE MOISTURE CONTENT OF 3.4 PERCENT

FIG. 4. MOISTURE DENSITY RELATIONSHIP AND COMPACTIVE EFFORT DENSITY RELATIONSHIP FOR GRAVEL (after Clark)

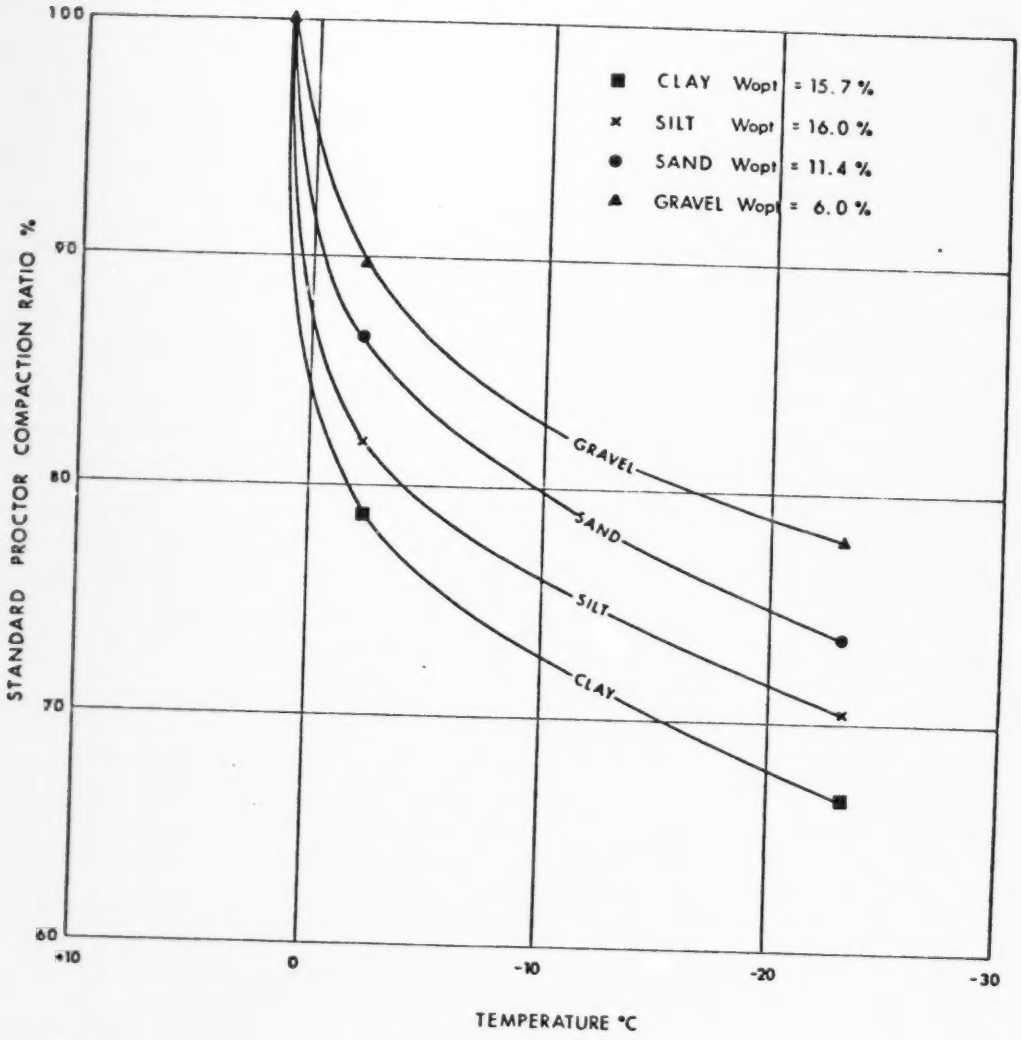


FIG.5. STANDARD PROCTOR COMPACTION RATIO
VS.
TEMPERATURE FOR FOUR SOIL TYPES

(after Clark)

Compactive Energy

The results obtained by Clark (4) are reproduced in Figures 1 to 4 of this report. It can be seen that the dry density increases for both frozen and unfrozen soil as the compactive energy increases. In general, the dry density was found to increase in the order of 5 to 10 percent by doubling the standard Proctor compactive effort. Similar results were recorded by Heiner (6). This increase in density was most pronounced with increasing water content presumably due to the breakdown of the frozen lumps.

Additives

A comprehensive study of the use of calcium chloride added to a silty sand was reported by Haas, Alkire, and Kaderabek (7). This study made a quantitative assessment of both freezing point depression and its effect on the compactability of soil. The authors found that the addition of 2 to 3 percent calcium chloride (by dry weight of soil) to a silty sand at a temperature of -7°C resulted in a Standard Proctor compaction ratio of at least 97 percent.

In comparison, the same soil at -7°C but with no additive had only 77 percent compaction ratio. These results are illustrated in Figure 6.

In practice, the inclusion of additives for compaction improvement has not been used to a large extent. It has been found to be a costly solution principally in the activity of mixing the additive into the soil. It has been concluded by Clark and Burwash that the effect of increased compactive effort is probably more economical than the use of an additive.

Methods of Compaction

Laboratory compaction tests performed by Heiner (6) indicate that the most important procedural factor in the compaction process is the total compactive effort rather than variations in the method of applying the energy. In addition, vibratory compaction was investigated with the results that, in all cases, the vibration tests gave a lower compaction ratio than the modified Proctor method. It would appear from the tests that the falling weight method of compaction produces a higher density due predominantly to breakdown of the frozen soil lumps in comparison to the vibrating method where compaction is achieved mainly by relocation of the soil lumps with no significant particle breakdown. No information was provided in the effect of varying vibration frequency.

Engineering Applications

There are numerous references in the literature pertaining to the use of frozen fill in engineered structures. These include the use of frozen fill in berms beside highway fills in Alaska (8); in highway fills and water retaining dykes in Northern Manitoba (9); to a

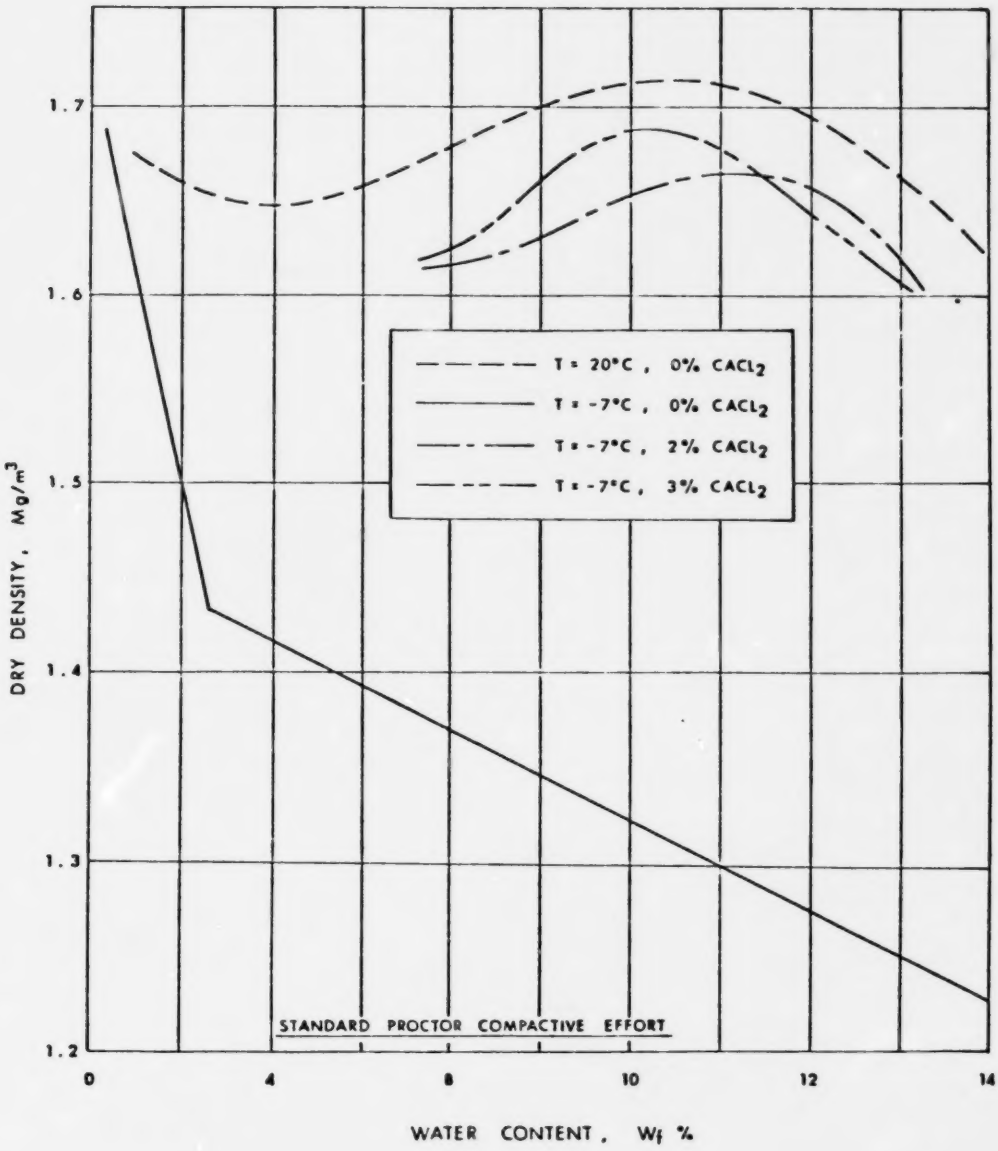


FIG. 6. RELATIONSHIP BETWEEN DRY DENSITY, WATER CONTENT, TEMPERATURE AND $CACl_2$ ADDITIVE

(after Haas et al)

limited extent in the James Bay projects in Northern Quebec (10); in the northern airfield program carried out by the Department of National Defence (11), and recently in a test embankment constructed by Public Works Canada at Inuvik (12). The large earth dams in northern Canada and Russia are usually constructed of material which is unfrozen (13). It is of some interest to note that the extensive literature from Russian sources on the excavation of frozen soils is in some contrast with their practice of compacting only unfrozen fills, sometimes at temperatures as low as -40°. They subsequently make extensive use of seasonally operated cooling units (SOCU's or thermosiphons) to improve the stability, settlement performance and watertightness of water retaining structures. The use of frozen soils in fills is mostly limited to granular soils, in which water and ice contents are usually quite low and reasonable densities can be achieved by additional compactive effort.

There are three main types of projects which have used frozen soils (i) water retaining structures such as dams and dykes, (ii) highway embankments, and (iii) compacted fill pads for airstrips, drilling rigs, pipelines, etc.

In the case of water retaining structures, normal construction specifications forbid the use of frozen fill, or the placement of fill on frozen ground (L'Ami, McPherson). Despite this, frozen soil has been permitted in non-critical sections of the South Saskatchewan Dam (L'Ami, Adams); in the Kettle, Kelsey, Long Spruce and Limestone dams and dykes belonging to Manitoba Hydro (L'Ami, Ellis, Smith, McPherson, Matheson, Keil); and to a very limited extent in the James Bay Project of Quebec Hydro (Pare), and at Cornwall and Darlington for Ontario Hydro (Adams). In these cases, construction consisted of late-season, low-temperature placement of granular fill with low moisture content. In most cases, particularly those in Manitoba, the fill was excavated unfrozen from the borrow pit during cold weather, transported in heated haul trucks, and compacted quickly using only the truck tires themselves or bulldozer tracks. Careful organization of continuous excavation, short haulage distances and fast compaction in carefully controlled lifts produced good performance. On the other hand, however, it has been pointed out that the relatively low densities usually achieved in compacted fills may actually be helpful in producing non-brittle materials in situations where degrading permafrost foundations may lead to significant shearing strains in water retaining dykes.

In the case of highway construction, the problems are rather less clear. In Manitoba, plastic fill used in the Thompson Highway desiccated over a period of just a few years to a moisture content below its plastic limit, and good performance resulted. However, on the Gillam-Split Lake Highway, this did not happen, and troublesome soft spots remain (Young, van Cauwenberghe). Associated problems relate to detailed design and scheduling of culvert crossings, high groundwater levels in organic terrain, and frost heave problems in long cold winters, even where the permeability is low (Konrad).

Placement of ripped, frozen, granular fill and clay shale on the Dempster Highway appears to have been largely successful after an initial period of extra maintenance (Kenyon). The test fills at Inuvik for DPW represent an important approach to developing an understanding of the behaviour of different types of fill in highway embankments. It is important that every opportunity is taken to maximize the amount of useful knoweldge that can be gained from these fills.

Work has also been done in the northern U.S. (Haas, Michigan Tech. Univ.) to investigate the effect of soil type and temperature on placement density, and the use of various chemical additives to lower the freezing point of the soil. Further research is needed. We have been actively encouraged to pursue studies of the relationship between the fill type and fill properties.

Further north, the problem is rather different. Here the winter seasons are longer, the fill temperature is lower, and summer construction is difficult in organic terrain. The winter period is extensively used for constructing pads for drilling platforms, pipelines, local access roads, and airfields. In these cases, the permafrost front often moves up into the fill, and good performance results (McKay, Wojcek).

Excavation is done in one of three ways (a) by face excavation with the base of the borrow pit below the frost line (McPherson), (b) by stripping, thawing and scraping shallow layers from the borrow area (Wojcek), and (c) by blasting (Jarrett). Canadian practice seems to favour the first method, although the second method has been used where the frost depth is large. Blasting in non-indurated materials is usually inefficient and expensive.

Compaction of granular soils is usually described as being relatively successful, although the procedures used vary somewhat. In most cases, compaction occurs simply from the rubber tires of the haul trucks or from caterpillar tracks. In other cases, sheepsfoot rollers have been used, although their success has been questioned. The detailed geometry and stress level of the roller feet become important. Vibratory rollers seem to have been used to only a very limited extent. Specifications usually call for only a relatively low level of compaction - perhaps reflecting the reality of the situation - and engineering details are designed with this in mind. Indeed, in some applications, for example in culverts and dykes on permafrost, over-compaction produces unwelcome brittleness (Baker, McPherson) which may lead to problems if differential settlements occur in the foundation soils.

Clay soils have been used less frequently. Their higher moisture contents cause them to be harder at the time of excavation, and more difficult to compact. Subsequent thaw-settlements are often uneven, and produce soft, compressible fills. Relatively little systematic work appears to have been done on processing the soils after excavation

to produce material which can be more effectively compacted (Wardrop, Winnipeg; McPherson, Pare).

In sum, designers and contractors want to be able to excavate and compact construction soils during cold weather in a wide variety of project types in many areas of Canada. These range from municipal projects in Southern Canada, to major resource developments in the far North. Research and development is needed into equipment design and the quality of compaction which can be obtained.

Our search produced the bibliography which appears at the end of this report. It is divided into two parts consisting firstly of a limited number of new references dealing with the compaction of frozen soils, and secondly, publications dealing with excavation techniques. It has not been possible in the time available to acquire and inspect all of the references. However, those appearing in major Journals and Conferences, and a significant proportion of the remainder have been examined.

The review of existing practice has shown that designers and contractors are well aware of the problems associated with incorporating frozen fill into embankments. Nevertheless, it is also very clear that production schedules, the need for greater utilization of equipment, and increasing construction activity in Northern Canada are all dictating a need for longer construction seasons, and the placement of fill at lower temperatures.

Our studies suggest that in addition to the participants in this study, the major workers in the compaction of frozen fill are W.M. Haas at Michigan Technical University, T.H.W. Baker at DBR NRC Ottawa, J.G. McPherson at Acres Consulting Services, Winnipeg, R.D. Cook, DPW Edmonton and F.E. Crory, U.S. CRREL, Hanover, N.A. As regards excavating, we draw attention to the work by Mellor and by Foster-Miller in CRREL reports, and the Russian references listed in Appendix A (ii). A strong capability for development of unique equipment exists with Canadian firms such as Canadian Foremost Ltd., Bombardier Inc. and Champion Road Machinery Ltd. Invaluable experience with Arctic construction projects, including large earthworks, has been gained by several contracting firms such as those of the Tower group of companies in Montreal.

In summary, the interviews with several groups, equipment manufacturers and contractors confirm the urgent need for improved capability to excavate frozen soil and to construct stable earthworks from frozen soil. The development of the technology and equipment to efficiently and economically do so would represent a major technological breakthrough. Most of those interviewed demonstrated the experience and willingness to participate in the development of the capability.

3 RECOMMENDATIONS

Given 1) there is a clearly identified need to develop and perfect techniques for excavating and compacting frozen soil;

2) that Canadian equipment manufacturers have been identified which have the engineering capability and interest, but not the financial resources, to design and build equipment for such purposes; and

3) it is in the national interest to help Canadian manufacturers and engineers meet the challenge of northern development and winter works throughout Canada

it is recommended that a program of studies and field trials be initiated and financed which will put Canada in the forefront of earthwork engineering in freezing and frozen soils.

The aims of the proposed project are:

1) to develop the most efficient technique to excavate, process and compact frozen soil

2) to develop Canadian manufactured equipment which will perform the identified function in a cold environment

3) make Canadian engineers and contractors aware that techniques and equipment have been perfected to carry out earthworks in frozen soil year round.

A combination of laboratory testing, field trials, equipment development, and demonstrations is envisaged for the project. In addition to satisfying the needs for cold weather work with frozen soil in Canada, the project will put Canadian manufacturing concerns and consulting engineers in a commanding lead with respect to the provision of equipment and services of this nature worldwide.

The project will be carried out in a number of phases; the exact number and content of each phase will be determined by the contractor for Phase I whose suggested terms of reference are outlined in Appendix B. For the purpose of this report, it is assumed that the project will be in five phases as outlined in Figure 7. The project will take 2 1/2 years from start to completion; the major component of funding will be required in the second year according to the cost estimates of Figure 7

While ideally the same team of engineers and designers should be responsible for and follow the project through its various phases to completion, it would be possible to divide the project up into a number

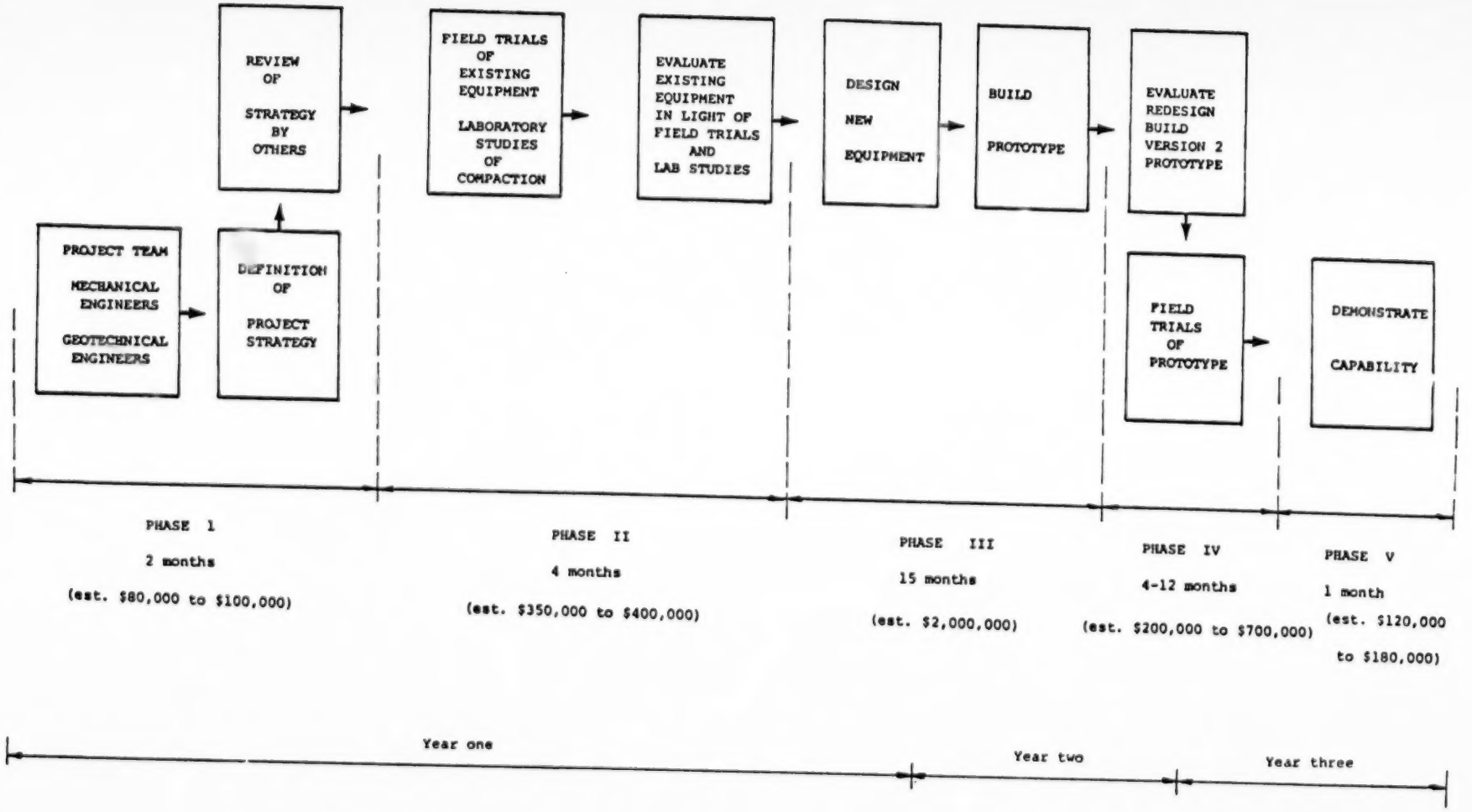


FIG. 7 DEVELOPMENT OF CANADIAN MACHINERY AND TECHNIQUES FOR FROZEN SOIL EARTHWORKS

of discrete parts which could be contracted out on an individual basis. Draft terms of reference for contractors to carry out Phase II for example either whole (Appendix C) or as three discrete parts (Appendix D) have been prepared.

No attempt has been made to prepare terms of reference for Phases III, IV and V since the make up of these phases will depend on the findings of Phase I and II.

While Figure 1 is reasonably self-explanatory, the following paragraphs give additional details of the proposed five stage strategy to develop frozen soil earthwork capability in Canada.

Phase I

The initial step would see the assembly of a project team which ideally would consist of individuals from a partnership of firms making up a consortium to undertake the entire project. (At this time it is envisioned that a consortium of a geotechnical consulting firm, a Canadian equipment manufacturer and a consulting mechanical engineer would be awarded the contract to carry out this work.) A team of two mechanical and two geotechnical engineers is proposed, with one of the geotechnical engineers being the project leader/manager.

The first task of the project team would be to prepare a strategy for the project including the delineation of responsibilities and a work plan for the project. The work plan would be complete in all aspects including identification of possible sources for services and goods, a schedule of events, and the establishment of cost control. An important task of the team would be to identify knowledgeable individuals (knowledgeable in northern construction, cold climate operation of equipment, earth moving and compaction, and the quality control of earthworks) to serve as a peer review committee. The peer review committee would be asked first of all to review and comment upon the project strategy put forward by the project team, and then secondly to meet with the project team to modify the strategy in the light of suggestions made by the peer review committee members.

Phase II

While the remainder of the project will, of course, follow the strategy arrived at jointly by the project team and the peer review committee, it is reasonable to assume that the project will follow, in a broad sense, the guidelines put forward in Figure 1. These guidelines assume that it will be worthwhile to measure the capability of existing equipment to serve as a point of departure, or benchmark, for the study. Careful observation of the performance of existing equipment by the project team and equipment designers will certainly serve as input for the eventual design and development of more suitable equipment. Site selection for the trials and the logistics of the trials will be handled by the geotechnical manager in the project team. The geotechnical consultant will also be responsible for measuring the performance of the equipment in terms of the end product, that is the

state of the frozen soil after it has been excavated, processed and compacted by most suitable existing equipment.

In parallel with the field trials of selected existing equipment, it is intended that a laboratory study will be carried out to determine the best way to compact frozen soil. The 'best way' determination will build on the prior work of other researchers, previously described but the experiments will, of necessity, be of a larger scale, both in terms of physical size as well as in terms of variables to be considered. Work carried out today emphasizes the importance of being able to produce frozen material of a size and gradation that will compact readily. It is also important to overcome ice bonding between frozen soil particles or lumps during the compaction process. Both the study of gradation (size) and the study of ice bonding will require tests at a scale which is representative of the field situation. Project funds are required to purchase the equipment necessary to carry out the proposed laboratory studies, as well as to pay for the labour involved in performing the tests and analyzing the results.

Phase III

Given the results of the field trials and the laboratory studies, performance specifications for new equipment can be prepared. Equipment designs which meet the performance requirements can then be developed as the next step in the events leading up to the successful completion of the project. Given the requirement that the new equipment (most probably an excavator/processor machine and a separate compaction unit) 1) be serviceable in extreme cold as well as 2) perform in the prescribed way, it is thought that the design/build phase of the project will be the most costly component. Considerable mechanical inventiveness will be required. In addition, the selection of special cold temperature materials will mean that fabrication costs will be high even though every effort will be made to keep the equipment simple.

Phase IV

Field trials of the new equipment must be carried out, preferably at one or two sites in addition to the site of the trials of existing equipment. Here, the trials must fit into the winter 'window', that is to say, the time of year when the soil is frozen and at or near its lowest annual temperature and air temperatures are seasonably low. The ability of the equipment to excavate and compact soil will be documented, including the serviceability of the equipment in the cold as well as the condition of the finished product (the compacted soil).

Provision should be made in the project budget for modification to the equipment and further field trials as required. Hopefully at the end of one or two 'iterations' of 'modification-field trials', the definitive production model of the equipment will form the centre-piece for the final phase, Phase V.

Phase V

Given the natural skepticism with which many Canadians greet the announcement of innovative ideas or techniques, it is important that those involved in designing, carrying out or controlling earthwork activities be shown that the new equipment and techniques really work in frozen ground. It is recommended that demonstrations be performed at, say, five selected locations across Canada. If the demonstrations were to be carried out in winter, then they could be held in the south of Canada close to metropolitan centres. In this way it would be relatively easy to get large numbers of engineers, contractors and public works officials to attend. Arrangements for making a suitable terrain available, assembly of equipment, and the publicity form part of the project, along with the costs of carrying out the demonstrations.

Phase V sees the end of the proposed project. The future would then be in the hands of the engineering profession and in the hands of the equipment manufacturers. The profession must encourage, demand and specify frozen soil earthworks and the equipment manufacturers must build the necessary machinery to meet the engineer's requirements. Competition among earth moving contractors to use the most efficient machinery will ensure that the new equipment is purchased for use on the projects.

For at least one demonstration, representatives of Canada's foreign trade departments must be invited to participate. In this way, Canada's expertise in frozen soil earthworks can be made known abroad.

The total estimated cost of the project is from $2.8 million to $3.4 million with costs being apportioned to the various phases as indicated in Figure 7.

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1.0 AIR SYSTEMS

- Cold Air Diverters (Air Cleaners)
- Air Cleaners - Cyclone Type
- Air System Dryer - Automatic
- Tiled Reservoirs
- Metal Discharge Flex Lines
- Heated Expello Valves
- Special Intake Valves
- Alcohol Evaporator
- Low Temperature Hoses
- After Coolers

2.0 BRAKE SYSTEMS

- Diaphragm Material Change
- Orchelin Levers on Hand Brakes
- Brake Hose - Low Temperature
- Heated Relay Valves
- Non-Looped Air Lines
- Brake Materials
- Lubrication
- Disc in Lieu of Drum Type
- Shielding
- Jacob Brakes - H.D. Mobile Equipment

3.0 CAB DESIGN

- Insulated and Noise Suppression
- Pressurized Heating Systems
- Extra Heater Capacity
- Partial Fresh Air Circulation
- Fans in Addition to Defrosters
- Heated Mirrors
- Double Glazing in Fixed Windows (excluding windshields)
- All Controls Arranged for Arctic Clothing
- Non-Skid Tread Steps
- Non-Glare Hood Designs
- Escape Hatch - Large Equipment
- Hazard Lights
- Exterior Lights
- Suspension Type Operators Seat (Large Equipment)
- Survival Equipment

4.0 COOLING SYSTEMS

- Fin and Tube Types Preferred
- Surge Tank Systems
- Shock Mounted and Additional Support
- Radiator Shutters (horizontal Vanes)
- Low Temperature Coolant (50% Ethylene Glycol or Dowtherm)
- Low Temperature Hose
- Alligator Hose Clamps
- Shroud for Fan

5.0 ELECTRICAL SYSTEM

Wiring Insulation Material
Natural Rubber Preferred
Heavy Duty Alternators
(brushless, extra capacity, sealed)
Heavy Duty Batteries
Insulated Battery Boxes
Battery Heaters
Manual Circuit Breakers
Ignition System - Copper in Lieu of Carbon Filled
Heavy Duty Battery Switch
Low Oil/High Water Shut Down Control
Series - Parallel Starter System

7.0 FULE AND LUBRICATION SYSTEMS

Fuel Tank Heating Systems (location or heaters)
Fuel Pumps (excess delivery system)
Insulated Lines
Tank Materials (tern plate preferred)
Vented Breather System
Heavy Duty Filler Caps
Fuel Pump Valve
Central Lubrication System
Low Temperature Oils and Grease

6.0 ENGINE AND TRANSMISSION SYSTEMS

Water Cooled Four Cycle Diesel Engines for Mobile and Construction Equipment Preferred
Water Cooled Two Cycle Diesel Engines may be Used for Gensets, Compressors, et al
Low Temperature Diesel Fuels
Low Temperature Lubricating Oils
Fast Idling Hand Control
Fuel Filters - Primary and Secondary
Water Separator
Thermostatic Fans (Reversible)
Engine Pan Covers
Circulating Block Heater
Exterior Circulation System
Starting System Assist (Ether or Pre-Heat)
Shielded Oil Immersion Heater
Compression Release - Manual
Excess Fuel Pump Delivery System
Automatic or Power Shift Transmission Preferred
Type C Transmission Fluid
Vented Breathers
Minimize Low Temperature - Exhaust Fog
Remote Mount Filters and Coolers for Accessibility
Parallel Cooler Systems for Engine and Transmissions

8.0 HYDRAULIC AND HYDROSTATIC SYSTEMS

Preferred Type C Fluid - Standardize
Hoses - Low Temperature and Fluid Resistant
Hydraulic Reservoir - Common, Excess Capacity, Aeration
Primary and Secondary Filters
Low Temperature Hose Fittings
Recirculating Systems
Heat Traced where Recirculation not practical
Seals - Arctic Type

9.0 LOAD CARRYING SYSTEMS

Exhaust Heating
Large Diameter Live Rolls
Flush Mounted Gin Rolls
High Strength U-Bolts and Sleepers
Reinforced Rear Winch Mounting
Folding Fifth Wheels
Replaceable Deck Materials
Conveyor Materials

10.0 MECHANICAL DRIVE SYSTEMS

Oil Bath Hubs
Low Temperature E.P. Oils
Recirculation Systems
Leather Seals
Vented Breathers
Low Temperature Structural
Mounting Systems

11.0 METALLURGY

The effects of severe low temperatures on Arctic operations relative to metallurgy must always be examined prior to the selection of equipment destined for Arctic use.

The deterioration of the impact properties of mild steel at low temperatures is well documented, hence the use of mild steel is generally discouraged for Arctic operations, especially where impact loads occur.

Special materials and design techniques have been developed to ensure that equipment can be operated successfully under the most severe Arctic winter conditions with ambient temperatures as low as -51°C (-60°F).

12.0 STRUCTURAL

- Side Booms
- Live Rolls
- Wear Parts
- A-Frames
- Gin Poles
- Swivel Pintle Hooks
- Main Frame Designs
- Deck Designs
- Support Member - Conveyors
- Welding Techniques and Materials

13.0 TIRES AND TUBES

- Radial Tires Preferred
- Non-Directional Tread Patterns
- Tube Applications
- Tube Materials
- Tire Construction
- Rim Size and Design
- Cast Spoke Designs

14.0 TRACKS AND ROLLERS

- Grouser Bars
- Urethane Sprockets - Flexible Tracks
- High Impact Sprockets - Hard Tracks
- Low Temperature Rollers
- Heavy Duty Track Pads
- Flat Grouser Bar Design - Flexible Tracks
- Lubrication
- Pin Connectors
- Snow and Dirt Shields

15.0 WINCH SYSTEMS

- Sheave Design
- Hydraulic Actuated
- Brake Procedures and Actuation
- Longest Line Length Installed
- Full Power Reverse
- Line Hardware
- Accessories

PHASE 1

COLD REGIONS ENGINEERED EARTHWORKS

OUTLINE TERMS OF REFERENCE TO DEVELOP A WORK PLAN

1. PROGRAM OBJECTIVES

Develop a strategy by which Canadian cold region earthworks capability can be assessed and improved to meet present and future needs.

2. CONTEXT

There is a demonstrated need to carry out earthworks using frozen soil in wintertime in Canada. Not only will plant and manpower be used more efficiently if earthworks can be carried out year round, but access to many northern areas is only feasible in wintertime when the ground is frozen.

Research has shown that it is feasible to excavate, process and place frozen soil. Additional research is required to define the best and most efficient way to perform frozen soil earthworks in the field. Existing earth moving equipment must be assessed in the light of this definition and new equipment must be designed and built to improve performance.

An opportunity exists for Canadian manufacturers to produce excavation and compaction equipment for frozen soils earthworks since no specialized equipment of this type is produced anywhere in the world.

3. KEY TASKS

(a) Review the report prepared by Golder Associates and others entitled "Cold Regions Engineered Earthworks" Transport Canada Report No. TP 4424E.

(b) Prepare an overall work plan which will 1) enable current Canadian capability to carry out frozen soil earthworks to be assessed, 2) initiate the required laboratory studies of frozen soil compaction, and, 3) lead to the design, manufacture and testing of Canadian built frozen soil excavation, processing and compaction equipment.

(c) Assemble a committee made up of knowledgeable individuals to review the work plan.

(d) Modify the work plan in accordance with the recommendations of the peer review committee.

(e) Prepare detailed requests for proposals for each of the various phases or parts of the work plan developed in (b).

4. REQUIRED END PRODUCT

Report giving 1) a work plan for establishing Canadian equipment and engineering capability to perform cold regions earthworks, 2) draft requests for proposals which can be used by the Department of Supply and Services to enable the work plan to be executed.

5. TIMING/NOTIONAL BUDGET

2 calendar months/8-10 man months

6. CONTRACTOR CAPABILITY

(a) Geotechnical engineering
(b) Mechanical engineering
(c) Earth moving equipment design and operation expertise
(d) Earthworks control expertise
(e) Northern engineering/cold climate expertise

PHASE II

COLD REGIONS ENGINEERED EARTHWORKS

OUTLINE TERMS OF REFERENCE

1. PROGRAM OBJECTIVES

   (a) To conduct field trials of existing excavation and compacting equipment in cold temperatures and frozen ground to assess performance.

   (b) To carry out laboratory studies of the processing and compaction of frozen soil.

   (c) To combine the findings of (a) and (b) and suggest improvements to field equipment and plant to enable frozen soil earthworks to be carried out in winter in any part of Canada.

2. CONTEXT

   There is a demonstrated need to carry out earthworks using frozen soil in wintertime in Canada. Not only will plant and manpower be used more efficiently if earthworks can be carried out year round, but access to many northern areas is only feasible in wintertime when the ground is frozen.

   Research has shown that it is feasible to excavate, process and place frozen soil. Additional research is required to define the best and most efficient way to perform frozen soil earthworks in the field. Existing earth moving equipment must be assessed in the light of this definition and new equipment must be designed and built to improve performance.

   An opportunity exists for Canadian manufacturers to produce excavation and compaction equipment for frozen soils earthworks since no specialized equipment of this type is produced anywhere in the world.

3. KEY TASKS

   (a) Review the report of Phase I of the project.

   (b) Select a site at which field trials of existing excavation and compaction equipment can be carried out in freezing weather and on frozen soil

(c) Contract with earthmoving contractors to supply selected pieces of earthmoving equipment and perform field trials at the selected site at the appropriate time of year.

(d) Observe the performance of the equipment in (c) and prepare a report.

(e) Specify a series of laboratory tests to be carried out to study the best way to process and compact frozen soil in the field.

(f) Carry out or arrange for the tests in (e) and prepare a report.

(g) Combine the observations concerning the performance of existing equipment (d) with the results of the laboratory simulations of compaction (f) and prepare a report which suggests ways in which existing equipment can be altered or new equipment built to carry out frozen soil earthworks in cold temperatures.

4. REQUIRED END PRODUCT

A report which specifies the equipment required to carry out frozen soil earthworks in the winter.

5. TIMING/NOTIONAL BUDGET

4 calendar months/25 to 28 man months
Subcontracting costs including living expenses $125,000 to $150,000
Equipment purchase/rental $25,000 to $30,000

6. CONTRACTOR CAPABILITY

(a) Geotechnical engineering
(b) Mechanical engineering
(c) Contract preparation and management expertise
(d) Earthmoving equipment selection and design expertise
(e) Earthworks control expertise
(f) Soil laboratory facilities and soil testing expertise for frozen soils.
(g) Northern engineering/cold climate expertise

PHASE II - PART A

COLD REGIONS ENGINEERED EARTHWORKS

OUTLINE TERMS OF REFERENCE

1. PROGRAM OBJECTIVES

To conduct field trials of existing excavation and compacting equipment in cold temperatures and frozen ground to assess performance.

2. CONTEXT

There is a demonstrated need to carry out earthworks using frozen soil in wintertime in Canada. Not only will plant and manpower be used more efficiently if earthworks can be carried out year round, but access to many northern areas is only feasible in wintertime when the ground is frozen.

Research has shown that it is feasible to excavate, process and place frozen soil. Additional research is required to define the best and most efficient way to perform frozen soil earthworks in the field. Existing earth moving equipment must be assessed in the light of this definition and new equipment must be designed and built to improve performance.

An opportunity exists for Canadian manufacturers to produce excavation and compaction equipment for frozen soils earthworks since no specialized equipment of this type is produced anywhere in the world.

3. KEY TASKS

(a) Review the report prepared as Phase I of the project.

(b) Select a site at which field trials of existing excavation and compaction equipment can be carried out in freezing weather and on frozen soil.

(c) Contract with earthmoving contractor to supply selected pieces of earthmoving equipment and perform field trials at the selected site and at the appropriate time of year.

(d) Observe the performance of the equipment on (c) and prepare a report.

4. REQUIRED END PRODUCT

A report which describes the ability of existing excavation and compacting equipment to handle frozen soil in winter.

5. TIMING/NOTIONAL BUDGET

4 calendar months/12-13 man months
Equipment purchase rental $120,000 to $150,000
Miscellaneous expenses $10,000 to $15,000

6. CONTRACTORS CAPABILITY

(a) Geotechnical engineering
(b) Mechanical engineering
(c) Contract preparation and management expertise
(d) Earthmoving equipment selection expertise
(e) Earthworks control expertise
(f) Northern engineering/cold climate expertise

PHASE II - PART B

COLD REGIONS ENGINEERED EARTHWORKS

OUTLINE TERMS OF REFERENCE

1. PROGRAM OBJECTIVES

To carry out laboratory studies of the processing and compaction of frozen soil.

2. CONTEXT

There is a demonstrated need to carry out earthworks using frozen soil in wintertime in Canada. Not only will plant and manpower be used more efficiently if earthworks can be carried out year round, but access to many northern areas is only feasible in wintertime when the ground is frozen.

Research has shown that it is feasible to excavate, process and place frozen soil. Additional research is required to define the best and most efficient way to perform frozen soil earthworks in the field. Existing earth moving equipment must be assessed in the light of this definition and new equipment must be designed and built to improve performance.

An opportunity exists for Canadian manufacturers to produce excavation and compaction equipment for frozen soils earthworks since no specialized equipment of this type is produced anywhere in the world.

3. KEY TASKS

(a) Review the report prepared as Phase I of the project.

(b) Specify a series of laboratory tests to be carried out to study the best way to process and compact frozen soil in the field.

(c) Carry out or arrange for the tests in (b) and prepare a report.

4. REQUIRED END PRODUCT

A report which describes 1) the laboratory tests carried out to process and compact frozen soil, 2) the results of the tests, and, 3) recommendations on how best to process and compact frozen soil in the field.

5. TIMING/NOTIONAL BUDGET

4 calendar months/12-13 man-months
Equipment purchase and rental $18,000 to $20,000
Miscellaneous expenses $6,000 to $8,000

6. CONTRACTORS CAPABILITY

(a) Geotechnical engineering
(b) Mechanical engineering
(c) Soil laboratory facilities and soil testing expertise for frozen soil.
(d) Northern engineering/cold climate expertise

PHASE II - PART C

COLD REGIONS ENGINEERED EARTHWORKS

OUTLINE TERMS OF REFERENCE

1. PROGRAM OBJECTIVES

To combine 1) the findings of field trials to assess the capability of existing earthmoving machinery to handle frozen soil in winter, with 2) the findings of laboratory studies to determine the best way to process and compact frozen soil in order to suggest improvements to field equipment and plant and soil handling techniques so that frozen soil earthworks can be carried out in winter in any part of Canada.

2. CONTEXT

There is a demonstrated need to carry out earthworks using frozen soil in wintertime in Canada. Not only will plant and manpower be used more efficiently if earthworks can be carried out year round, but access to many northern areas is only feasible in wintertime when the ground is frozen.

Research has shown that it is feasible to excavate, process and place frozen soil. Additional research is required to define the best and most efficient way to perform frozen soil earthworks in the field. Existing earth moving equipment must be assessed in the light of this definition and new equipment must be designed and built to improve performance.

An opportunity exists for Canadian manufacturers to produce excavation and compaction equipment for frozen soils earthworks since no specialized equipment of this type is produced anywhere in the world.

3. KEY TASKS

(a) Review the reports prepared as Phases I, IIa and IIb of the project.

(b) Suggest ways in which existing earthmoving equipment can be altered or new equipment designed and built to carry out frozen soil earthworks in cold temperatures.

4. REQUIRED END PRODUCT

A report which outlines the ways existing earthmoving equipment can be altered or new equipment designed and built to carry out frozen soil earthworks in winter.

5. CONTRACTOR CAPABILITY

(a) Geotechnical engineering
(b) Mechanical engineering
(c) Cold climate/northern engineering expertise
(d) Earthmoving expertise

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